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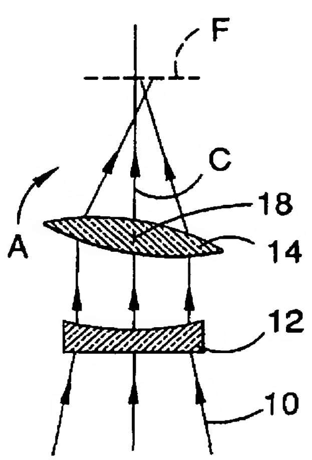
(54) **Title:** OPTICAL SYSTEM AND METHOD FOR PRODUCING IN FOCUS AND DEFOCUSED IMAGES



(57) Abstract: An optical system for an apparatus for producing phase images of an object is disclosed which includes at least one optical element, such as a positive lens (12) and a positive lens (14), or a spatial light modulator (15) or deformable mirror (60) are interposed in light transmitted from a light source (5) to a charge coupled device (20) in order to produce in focus and defocused images. In the case of the lenses (12) and (14), the lenses are manipulated in a non-translatory manner in order to change the focus of the light, and in the case of the spatial light modulator, processor (40) outputs signals to the modulator (15) to control the modulator (15) to change the wave front of light passing through the modulator to create the focused and defocused images.

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OPTICAL SYSTEM AND METHOD FOR PRODUCING IN FOCUS AND DEFOCUSED IMAGES

Field of the Invention

This invention relates to an optical system and method for producing focused and defocused images of an object. The invention has particular application to the formation of images required to produce a phase image of the object.

Background of the Invention

It is known that a phase image of an object can be generated by quantitative determination of the phase of the radiation wave field emanating from the object. In International Patent Application No. PCT/AU99/00949 (Publication No. WO 00/26622) owned by The University of Melbourne, a method and apparatus for producing phase images is disclosed which involves solving the transport of intensity equation to enable both phase and intensity data relating to the object to be determined independently. This enables a phase image of an object to be produced which can provide detail, particularly in biological samples, which is not apparent when a conventional intensity or absorption image of the object is viewed. The contents of the above-mentioned International specification are incorporated into this specification by this reference.

The technique disclosed in the above International application involves taking images of the object. The images include an in focus image and at least one defocused image. Most preferably, at least three images are taken which include an in focus image and two defocused images. One of the defocused images is taken on one side of the in focus image and the other defocused image on the other side of the in focus image. The images are preferably captured by a camera in the form of a charge coupled device and in order to produce the

defocused images and the in focus images, at least one lens of an optical system for producing the images is translated in the direction of the light beam travelling from the object to the camera. The camera is usually located at the focal plane of the optical system. The lens system is translated away from the camera and towards the microscope, in the direction of the light beam until an electrical limit switch is activated. The lens system is then translated in the reverse direction for a pre-calculated distance and a first image is taken to produce a defocused image, the lens system is then translated in the direction of the light beam and a second image is taken by the camera to produce the in focus image at the focal plane, and then the lens system is again translated in the direction of the light beam so as to produce a second defocused image on the other side of the focal plane. The order of taking the in focus and defocused images is not essential and the images can be taken in any order provided it is known which image is the in focus image and which of the two images are the respective defocused images.

The translation of the lens system from one position to another to enable the three images to be taken generally is under the control of a mechanical system which physically moves at least one of the lenses of the optical system by translating the lens from one position to another position. The time taken to produce the three images of each sample is therefore significant from the point of view of analysis because it results in data required to produce the phase image taking a significant amount of time to capture and therefore the number of samples which can be processed and analysed in a given period is relatively small.

Summary of the Invention

The object of the invention is to overcome the above

problem.

The invention, in a first aspect, may be said to reside in an optical system for producing in focus and defocused images of an object, including:

at least one optical element for imaging a light beam emanating from the object onto a charge coupled device; and

manipulating means for performing a non-translatory manipulation of the optical element so as to cause an in focus and at least one defocused image of the object to be imaged sequentially on the charge coupled device.

Thus, according to this aspect of the invention the images can be sequentially produced but because the images are produced by manipulation of the optical element other than a translation the manipulation of the element can take place much more quickly thereby increasing the speed by which the images can be taken to enable a phase image to be produced.

Preferably the defocused image is produced by causing the optical element to perform a primary aberration on the light beam to produce the defocused image. Most preferably the primary aberrations are coma or astigmatism.

In one embodiment of the invention the at least one optical element comprises a positive lens and a negative lens separated from one another, one of the lenses being mounted for rotational movement about an axis transverse to the direction of propagation of the light beam from the object.

Preferably the positive lens is mounted for the rotational movement.

In another embodiment the optical element comprises a negative lens and an asymmetrical lens, and the asymmetrical lens is mounted for rotation about an axis which is parallel to the direction of propagation of the light beam from the object.

Preferably, in these embodiments of the invention, the system includes a processing means for processing data captured by the charge coupled device and the processing means compensating for known aberrations introduced into the images by rotational movement of the lens.

In a still further embodiment of the invention the optical element comprises a spatial light modulator and the spatial light modulator is manipulated by applying electrical signals to the modulator to cause a wavefront passing through the modulator to be distorted.

Preferably the spatial light modulator is controlled by application of current and/or voltage to the modulator so as to cause zero wavefront distortion to produce an in focus image, a known distortion such as a positive spherical wavefront distortion to produce a defocused image on one side of the in focus plane and applying voltage or current to the modulator to produce known distortions such as a negative spherical wavefront distortion of the beam to produce a defocused image on the other side of the in focus plane.

Preferably the optical system is included in an apparatus for producing phase images of the object which includes:

the said optical system and a light source for producing light which is transmitted through or reflected from the object and then through the optical system;

a charge coupled device for detecting the light; and

processing means coupled to the charge coupled device for receiving data relating to in focus and defocused images and for producing a phase image from the in focus and defocused images.

The invention may also be said to reside in a method of producing an in focus and defocused images of an object, including:

passing a light beam through or reflecting a light beam from the object;

causing the light beam to be imaged at a detector by an optical element; and

manipulating the optical element in non-translatory fashion so as to produce in focus and defocused images of the object on the detector.

In one embodiment of the invention the at least one optical element comprises a positive lens and a negative lens separated from one another, and the manipulating step includes rotating one of the lenses about an axis transverse to the direction of propagation of the light beam from the object.

Preferably the positive lens is mounted for the rotational movement.

In another embodiment the optical element comprises a negative lens and an asymmetrical lens and the manipulating step includes rotating the asymmetrical lens about an axis which is parallel to the direction of propagation of the light beam from the object.

Preferably, the method also includes compensating for known aberrations introduced into the images by rotational movement of the lens.

In a still further embodiment of the invention the optical

element comprises a spatial light modulator and the manipulating step includes applying electrical signals to the modulator to cause a wavefront passing through the modulator to be distorted.

Preferably the spatial light modulator is controlled by application of current and/or voltage to the modulator so as to cause zero wavefront distortion to produce an in phase image, a known distortion such as a positive spherical wavefront distortion to produce a defocused image on one side of the in focus plane and applying voltage or current to the modulator to produce a known distortion such as a negative spherical wavefront distortion of the beam to produce a defocused image on the other side of the in focus plane.

In a still further embodiment of the apparatuses and method referred to above, the at least one optical element is a deformable mirror and the manipulating means comprises an actuator for deforming the mirror.

The actuating means may comprise a single actuator which causes the mirror to deform from a substantially flat mirror into a parabolic shaped mirror. However, if desired, multiple actuators could be used for causing the mirror to deform into other shapes. This aspect has application in correcting unwanted aberrations which may occur in the wavefront used to produce the in focus and two defocused images by slightly changing the shape of the mirror to correct for those aberrations.

The invention also provides an apparatus for producing a focused image and at least one defocused image of a sample, including:

a light source for providing a light beam to pass through, or to be reflected from the sample;

a detector for detecting the light beam after

passing through, or reflected from the sample;

an optical element in the path of the light beam; and

manipulating means for manipulating the optical element so as to produce an in focused image at the detector and at least one defocused image of the object at the detector.

Brief Description of the Drawings

Preferred embodiments of the invention will be described, by way of example, with reference to the accompanying drawings in which:

Figure 1 is a diagram illustrating the production of an in focus image according to one embodiment of the invention;

Figure 2 and Figure 3 show the production of defocused images according to the first embodiment of the invention;

Figure 4 shows the production of an in focus image according to a second embodiment of the invention;

Figure 5 and Figure 6 show the production of defocused images according to the second embodiment;

Figure 7 shows the production of an in focus image according to a third embodiment of the invention;

Figure 8 and Figure 9 show the production of defocused images according to the third embodiment of the invention;

Figure 10 is a schematic view showing an apparatus for producing phase images of an object; and

Figure 11 is a schematic view of a still further embodiment of the invention.

Description of the Preferred Embodiments

With reference to Figure 1, a light beam 10 emanating from an object (not shown) passes through a negative lens 12 so as to collimate the beam as shown by reference 10' and the collimated beam 10' then passes through a positive lens 14

so as to focus the beam 10 at a focal plane F at which a charge coupled device schematically indicated by reference 20 is located.

An in focus image of the object is therefore produced on the charge coupled device.

The lens 12 is a negative lens and the lens 14 a positive lens which are both spherical in nature and generally of the same magnitude of power. The lens 14 is mounted on a pivot 18 so that the lens 14 can pivot on the axis 18 which is arranged perpendicular to the direction of propagation of the beam 10 from the object to the charge coupled device 20.

As shown by Figure 2, by pivoting the lens 14 clockwise in the direction of arrow A, a positive coma of the focus light is produced which focuses the light on one side of central axis C and by rotating the lens 14 in the counterclockwise direction as shown by arrow B in Figure 3, a negative coma on the opposite side of the central axis C is produced. The positive and negative comas enable defocused images to be produced which are effectively defocused on respective sides of the focal plane F to provide data together with the in focus image which enables the transport of intensity equation to be solved to produce the phase image of the object.

The lens 18 may be rotated by a stepper motor 25 and suitable gear system which transmits drive to a support on which the lens is supported.

The data captured by the charge coupled device 20 is supplied to processor 30 so that the data can be manipulated and processed to produce a phase image of the object in the manner described in the above-mentioned International application.

Figure 4 shows a second embodiment of the invention in which the lens 12 is generally the same as the lens 12 of Figures 1 to 3. In this embodiment the lens 14 is an asymmetrical lens which can be of toroidal or cylindro-spherical shape. The lens 14 is mounted for rotation about a pivot axis 18 which is arranged parallel to the direction of propagation of the beam 10.

In the position of the lens 14 shown in Figure 1, an in focus image is produced at the focal plane F. By rotating the lens 14 about the axis 18 as shown by arrow C in Figure 5, the asymmetrical nature of the lens changes the configuration of the lens through which the beam 10 passes so that the effective focal point of the beam is beyond the focal plane F thereby producing a defocused image on the far side of the focal plane F. By continued rotation of the lens 14 about the axis 18 as shown in Figure C, the beam of light 10 is caused to pass through a differently shaped or thickened area of the lens so that the beam 10 is focused before the focal plane F so as to produce a defocused image on the other side of the focal plane F.

The defocus of the images according to the embodiments of Figures 1 to 3 and the embodiments of Figures 4 to 6 are, respectively, a primary aberration and, most preferably, coma as in the case of Figures 1 to 3, and astigmatism as in the case of Figures 4 to 6. These aberrations therefore enable the production of in focus images and defocused images to be produced to enable the data to be collected for solving the transport of intensity equation to produce the phase image of the object.

In the embodiments of Figures 1 to 3 and 4 to 6, the lens systems will introduce a known amount of aberration into the images which are produced, and the processor 30 compensates for the known aberrations by manipulating the

data to compensate for those known aberrations to thereby enable the focus and defocused images to be produced without aberrations introduced by rotation of the lenses 18.

Figures 7 to 9 show a third embodiment of the invention in which, rather than use lenses for the focusing of the beam 10, the lenses are replaced by a spatial light modulator 35 which is controlled by a processor 40 (which may be the same as the processor 30 or a separate processor) and which causes appropriate voltage and current signals to be applied to the modulator 35 so as to change the nature of the modulator 35 to in turn change the nature of the wavefront of the beam 10 emanating from the modulator 35.

In order to produce an in focus image at the CCD device 20 the spatial light modulator 35 is controlled as to produce zero wavefront distortion of the beam 10.

In order to produce a defocused image on the far side of the focal plane at which the charge coupled device 20 sits, the modulator 35 (as shown in Figure 8) is controlled by the processor 40 so as to introduce a known distortion such as a positive spherical wavefront distortion into the beam 10 to cause the beam 10 to focus passed the charge coupled device 20 and thereby produce the first defocused image.

In order to produce the second defocused image the modulator 35 is controlled by the processor 40 so as to introduce a known distortion such as a negative spherical wavefront distortion to the beam 10 so that the beam 10 focuses before the charge coupled device 20 (Figure 9) to provide a defocused image on the other side of the focal plane occupied by the charge coupled device 20. Thus, an in focus image and two defocused images on either side of the in focus image are produced by controlling the spatial

light modulator 35 to introduce distortion into the wavefront of the beam 10 as the wavefront passes through the modulator 35.

Figure 10 shows a schematic representation of an apparatus for producing phase images according to the preferred embodiment of the invention.

A light source 10 produces light preferably in the visible spectrum but which may also be in other parts of the spectrum and which penetrates the sample or object S. The light is then focused by the optical element 15 (which comprises any one of the systems described with reference to Figures 1 to 9) and which then focuses the light beam 10 onto charge coupled device 20. Data received by the charge coupled device 20 is transmitted to processor 30/40 which also controls the optical element 15. A monitor 50 is provided for viewing the image produced by the processor 30/40 in accordance with the algorithm of the above-mentioned International application.

The processor 30/40 can also control the optical element 15 by either rotating the lenses 14 of the optical element 15 (in the case of the embodiment of Figures 1 to 6) or providing appropriate signals to the spatial modulator 35 in the case of the embodiment of Figures 7 to 9, to produce the in focus and defocused images of the sample S to provide the data for enabling the phase image to be produced by the processor 30/40.

Figure 11 shows a still further embodiment of the invention in which like reference numerals indicate like parts to those previously described.

In this embodiment, light source 5 provides light which passes through sample S and is reflected by a deformable mirror 60 to CCD detector 20. The CCD detector 20 is

connected to processor 30/40 and the processor 30/40 is connected to monitor 50 in the same manner as the previous embodiments.

In order to obtain the focused and defocused images of the sample S, the deformable mirror 60 is controlled by an electrostatic actuator 70 which causes the mirror to deform into a parabolic shape.

If the mirror 60 is not actuated by the actuator 70, the mirror 60 would normally take up a flat shape, as shown by dotted line 60a in Figure 11. The processor 30/40 controls the actuator 70 to cause the mirror 60 to take up a parabolic shape by electrostatic attraction, so as to form an in focused image at the detector 20. By further controlling the electrostatic actuator 70 to pull the mirror 60 into a steeper parabolic shape, as shown by dotted line 60c, a defocused image on the near side of the in focused image can be obtained. By causing the electrostatic actuator 70 to pull the mirror 60 into a shallower parabolic shape, as shown in by dotted line 60b, a defocused image on the far side of the in focused image is obtained.

The processor 30/40 and actuator 70 can rapidly deform the mirror 60 and therefore the images can be captured extremely quickly.

Furthermore, if only a single actuator 70 is used, the deformation of the mirror is into parabolic shape as referred to above. However, if more than one actuator 60 is used, other more complicated shapes could be developed, and those additional deformations could be used to correct for aberrations which may be unwantingly introduced into the focused and defocused images.

Whilst in the embodiments shown, the processor 30/40 which

controls the CCD device 20 and display 50 is used to control a separate processor, or separate processors could obviously be used to control the actuator 70.

Since modifications within the spirit and scope of the invention may readily be effected by persons skilled within the art, it is to be understood that this invention is not limited to the particular embodiment described by way of example hereinabove.

Claims

1. An optical system for producing in focus and defocused images of an object, including:

at least one optical element for imaging a light beam emanating from the object onto a charge coupled device; and

manipulating means for performing a non-translatory manipulation of the optical element so as to cause an in focus and at least one defocused image of the object to be imaged sequentially on the charge coupled device.

2. The system of claim 1 wherein the defocused image is produced by causing the optical element to perform a primary aberration on the light beam to produce the defocused image.

3. The system of claim 2 wherein the primary aberrations are coma or astigmatism.

4. The system of claim 1 wherein the at least one optical element comprises a positive lens and a negative lens separated from one another, one of the lenses being mounted for rotational movement about an axis transverse to the direction of propagation of the light beam from the object.

5. The system of claim 4 wherein the positive lens is mounted for the rotational movement.

6. The system of claim 1 wherein the optical element comprises a negative lens and an asymmetrical lens, and the asymmetrical lens is mounted for rotation about an axis which is parallel to the direction of propagation of the light beam from the object.

7. The system of claim 1 wherein the system includes a processing means for processing data captured by the charge coupled device and the processing means compensating for known aberrations introduced into the images by rotational movement of the lens.

8. The system of claim 1 wherein the optical element comprises a spatial light modulator and the spatial light modulator is manipulated by applying electrical signals to the modulator to cause a wavefront passing through the modulator to be distorted.

9. The system of claim 8 wherein the spatial light modulator is controlled by application of current and/or voltage to the modulator so as to cause zero wavefront distortion to produce an in focus image, a voltage or current is applied to the modulator to produce a first known distortion to produce a defocused image on one side of the in focus plane and voltage or current is applied to the modulator to produce a second known distortion of the beam to produce a defocused image on the other side of the in focus plane.

10. The system of claim 9 wherein the first known distortion is a positive spherical wavefront distortion and the second known distortion is a negative spherical wavefront distortion.

11. The system of claim 1 wherein the optical element is a deformable mirror and the manipulating means comprises an actuator for deforming the mirror so as to produce the in focus and the at least one defocused image of the object.

12. An apparatus for producing phase images of an object which includes:

the said optical system according to claim 1 and

a light source for producing light which is transmitted through or reflected from the object and then through the optical system;

a charge coupled device for detecting the light; and

processing means coupled to the charge coupled device for receiving data relating to in focus and defocused images and for producing a phase image from the in focus and defocused images.

13. An apparatus for producing a focused image and at least one defocused image of a object, including:

a light source for providing a light beam to pass through, or to be reflected from the object;

a detector for detecting the light beam after passing through, or reflected from the object;

an optical element in the path of the light beam; and

manipulating means for manipulating the optical element so as to produce an in focused image of the object at the detector and at least one defocused image of the object at the detector.

14. The apparatus of claim 13 wherein the optical element comprises at least one lens and the manipulating means comprises means for rotating the lens about an axis transverse to the direction of propagation of the light beam.

15. The apparatus according to claim 13 wherein the optical element comprises an negative lens and an asymetrical lens, and the manipulating means comprises means for rotating the asymetrical lens about an axis which is parallel to the direction of propagation of the light beam.

16. The apparatus according to claim 13 wherein the

optical element comprises a spatial light modulator and the manipulating means comprises means for controlling the spatial light modulator to cause a wavefront passing through the modulator to be distorted.

17. The apparatus according to claim 13 wherein the optical element is a deformable mirror and the manipulating means comprises actuating means for deforming the mirror so as to change the shape of the mirror to thereby cause the in focused and the at least one defocused image to be imaged on the detector.

18. A method of producing an in focus and defocused images of an object, including:

passing a light beam through or reflecting a light beam from the object;

causing the light beam to be imaged at a detector by an optical element; and

manipulating the optical element in non-translatory fashion so as to produce in focus and defocused images of the object on the detector.

19. The method of claim 18 wherein the at least one optical element comprises a positive lens and a negative lens separated from one another, and the manipulating step includes rotating one of the lenses about an axis transverse to the direction of propagation of the light beam from the object.

20. The method of claim 19 wherein the positive lens is mounted for the rotational movement.

21. The method of claim 18 wherein the optical element comprises a negative lens and an asymmetrical lens and the manipulating step includes rotating the asymmetrical lens about an axis which is parallel to the direction of propagation of the light beam from the

object.

22. The method of claim 19 wherein the method also includes compensating for known aberrations introduced into the images by rotational movement of the lens.

23. The method of claim 19 wherein the optical element comprises a spatial light modulator and the manipulating step includes applying electrical signals to the modulator to cause a wavefront passing through the modulator to be distorted.

24. The method of claim 23 wherein the spatial light modulator is controlled by application of current and/or voltage to the modulator so as to cause zero wavefront distortion to produce an in phase image, a first known distortion to produce a defocused image on one side of the in focus plane, and a second known distortion of the beam to produce a defocused image on the other side of the in focus plane.

25. The method of claim 24 wherein the first known distortion is a positive spherical distortion and the second known distortion is a negative spherical distortion.

26. The method according to claim 12 wherein the optical element is a deformable mirror and manipulation of the deformable mirror comprises changing the shape of the deformable mirror so as to produce the in focused and defocused images of the object.

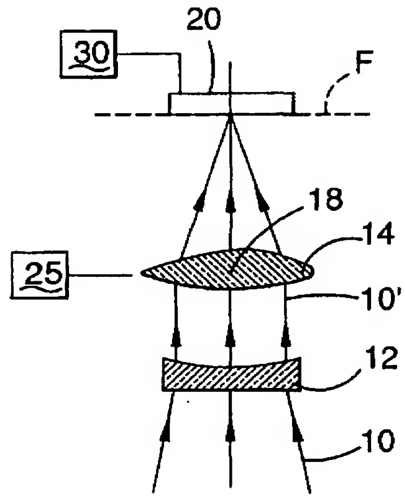

FIGURE 1

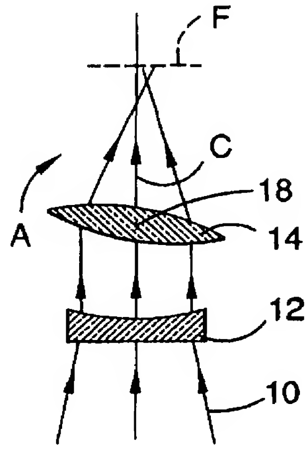

FIGURE 2

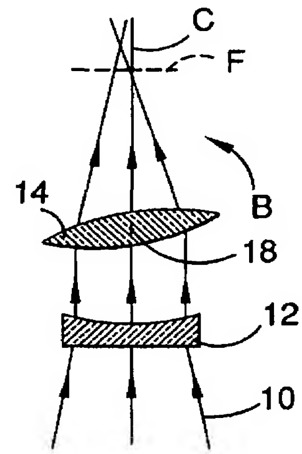

FIGURE 3

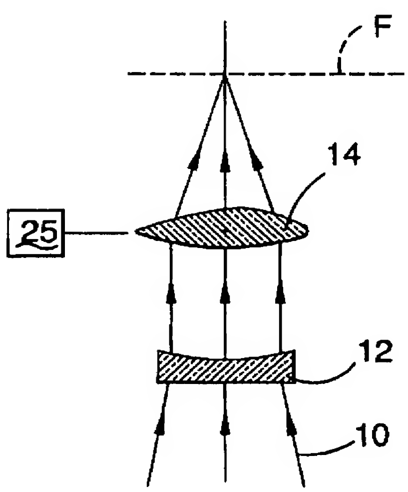

FIGURE 4

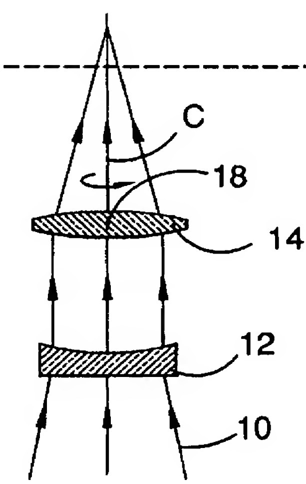

FIGURE 5

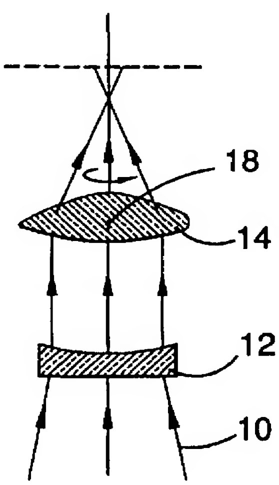

FIGURE 6

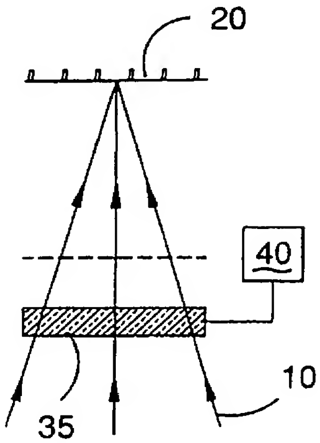

FIGURE 7

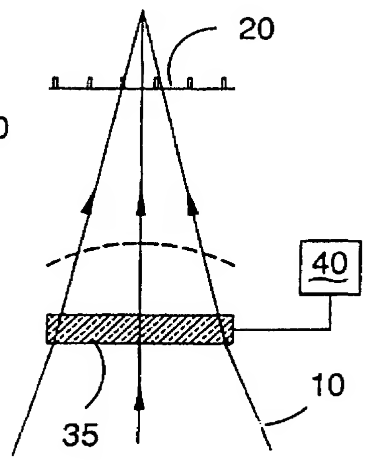

FIGURE 8

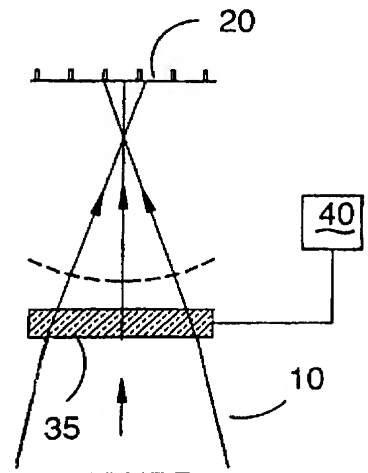

FIGURE 9

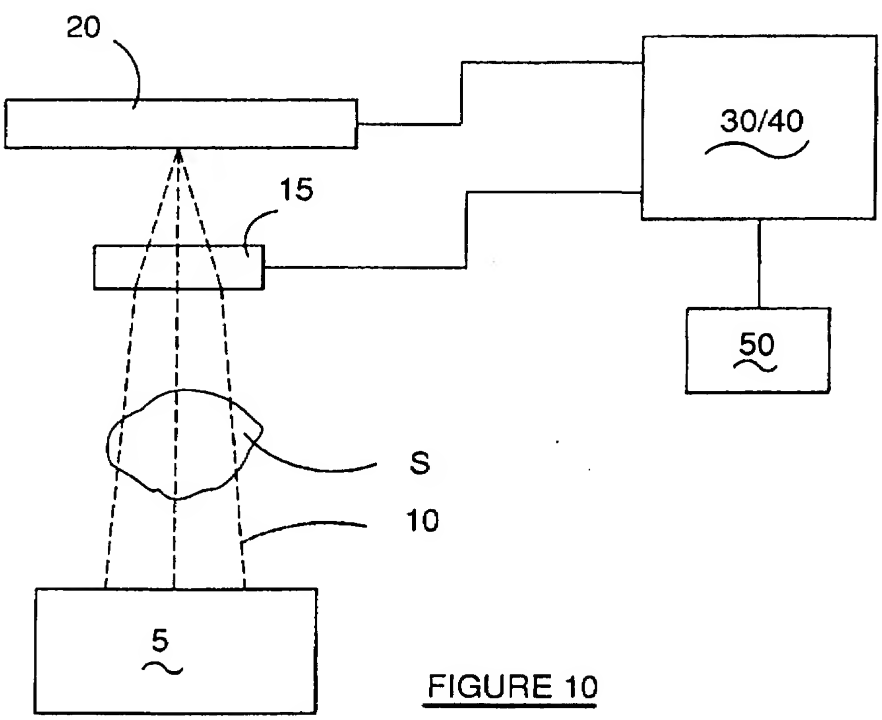

FIGURE 10

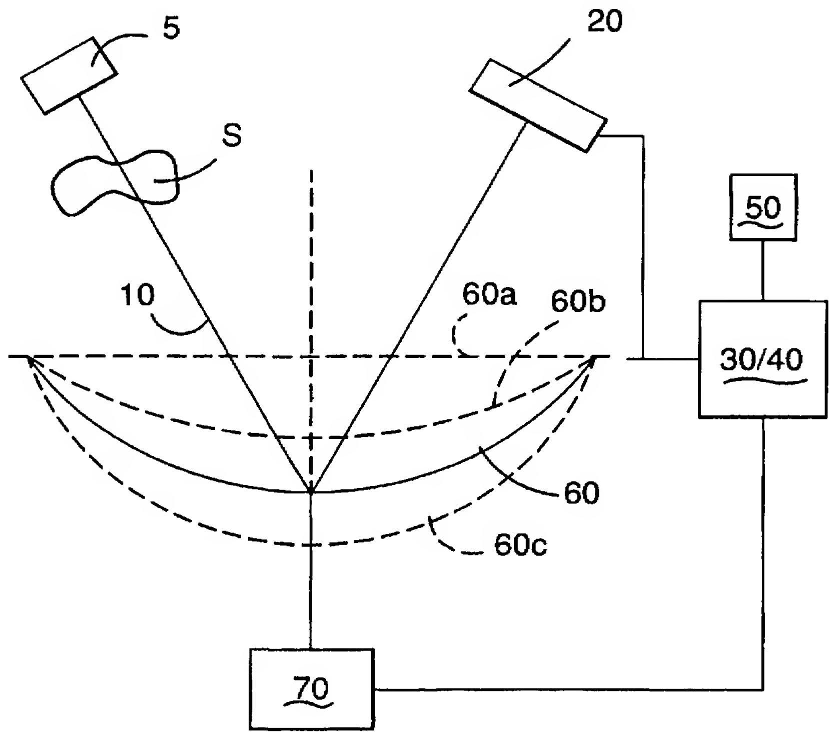

FIGURE 11

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU02/00968

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl. 7: G01J 9/00, G02B 7/04, 7/185, 27/46

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
DWPI, JAPIO IPC G02B, G01J 9/-, G02F 1/00, 1/19 with Keywords: focus; unfocus, defocus, out of focus, non focus, coma; lens, rotat, pivot; mirror, deform; spatial, modulat; wavefront, distort, control; hologra; phase, recover, retriev, reconstruct

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5260825 A (NAGANO et al.) 9 November 1993 Column 1 lines 12-33	1, 13, 14, 18
X	Derwent Abstract Accession No. 91-258872/35, Class P81, SU 1615655 A (LENINGRAD PREC MECH OPTI) 23 December 1990 Abstract	1, 11, 13, 17, 18
A	Patent Abstracts of Japan, JP 57-086815 (YOKOGAWA HOKUSHIN ELECTRIC CORP) 31 May 1982 Abstract	1-26

[X] Further documents are listed in the continuation of Box C [X] See patent family annex

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Date of the actual completion of the international search	Date of mailing of the international search report
6 September 2002	17 SEP 2002

Name and mailing address of the ISA/AU	Authorized officer
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU02/00968

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4236080 A (HEINZERLING) 25 November 1980 Whole document	1-26

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/AU02/00968

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
US	5260825	EP	388812	JP	3015015		
SU	1615655	NONE					
JP	57086815	NONE					
US	4236080	CA	1121917	DE	2805329	FR	2415401
		GB	2013068	GB	2089162	JP	54110795
		DE	2802746				

END OF ANNEX